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Low-Spin States From Decay Studies in the Mass 80 *Region*

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Neutron-deficient nuclei in the mass 80 region are known to exhibit strongly deformed ground states deduced mainly from yrast-state properties measured in-beam via heavy-ion fusion-evaporation reactions. Vibrational excitations and non-yrast states as well as their interplay with the observed rotational collectivity have been less studied to date within this mass region. Thus, several β-decay experiments have been performed to populate low-spin states in the neutron-deficient $^{80,84}Y$ and $^{80,84}Sr$ nuclei. An overview of excited 0^+ states in Sr and Kr nuclei is given and conclusions about shape evolution at low-spins are presented. In general, the non-yrast states in even-even Sr nuclei show mainly vibration-like collectivity which evolves to rotational behavior with increasing spin and decreasing neutron number.

Key words: low-spin states; neutron deficient nuclei; prolate deformation.

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1. Introduction

There is now extensive experimental evidence for large prolate deformation in the neutron-deficient Rb, Sr, and Y nuclei. For the even-even Sr isotopes, the evidence is based on experimental quadrupole moments extracted from level lifetimes [1,2] and excitation energies of the first excited yrast states [3]. In all these neutron-deficient nuclei, the underlying cause of the prolate deformation has been attributed to the population of strongly polarizing orbitals originating from the $d_{5/2}$ and/or intruder $g_{9/2}$ subshells and large gaps in the single-particle level energies.

The evolution of shapes of mass 80 nuclei from near-spherical to γ-soft and to well-deformed shapes as function of particle number and angular momentum has been investigated using different theoretical approaches [4-6]. In some cases, shape coexistence interpretations have been invoked to describe irregularities of the moments of inertia of some neutron-deficient even-even Se, Kr, and Sr nuclei at low spins [7]. For the even-even Sr isotopes the situation is quite complicated. Large prolate deformations as observed for $^{76,78}Sr$ are in agreement with most of the recent calculations while the nucleus ^{80}Sr is predicted to be spherical in the ground state with $\beta_2 = 0.053$ [6]. The ground-state deformation of $\beta_2 \approx 0.4$ as deduced from in-beam γ-ray experiments [1,2] is in contrast to recent results from fast beam laser spectroscopy [8] where the deduced mean charge radii indicate somewhat less deformed shapes for $^{78,80}Sr$. The neutron-deficient even-even Sr isotopes exhibit yrast level sequences (or moments of inertia) at low spins which show large deviations from the behavior expected for a rigid rotor, possibly indicating shape fluctuations. Thus, the issue of the rigidity of the shapes and the occurrence of co-existing configurations are not yet

resolved and have not been thoroughly addressed as many of the key states of interest are of low spins and of non-yrast nature, i.e., they are not well populated in the heavy-ion fusion reactions usually used for the in-beam studies.

Properties of nuclei along the $N = Z$ line are also of interest for the astrophysically relevant rapid proton capture (rp) process [9] which is thought to be one of the dominant energy sources in cataclysmic binaries like novae and x-ray bursts. The rp process is characterized by a sequence of fast proton capture reactions and subsequent β decay. Usually, the β decay is slow compared to the fast proton capture reactions. Waiting points can develop where the proton capture is compensated by inverse photo-disintegration or where single proton capture is inhibited at the proton-drip line. The lifetimes of these waiting-point nuclei are determined by the β decay of the ground state or thermally excited states. Thus lifetimes of ground states and/or β-decaying isomeric states in the vicinity of the proton-drip line are important input parameters for calculations of nuclear synthesis, luminosity, and time scale [10]. Nucleosynthesis at the extreme temperature and density conditions associated with such events may well proceed beyond the doubly-magic ^{56}Ni [11].

Only few alternative probes are available for investigating non-yrast states in nuclei far from stability. The most useful is the careful investigation of the β decay from a higher-Z parent nucleus. The parent spins are usually low so a large number of non-yrast states is expected to be populated when the decay energy is large. For a successful β-decay experiment sufficient production of the parent nuclei is needed. Far from stability, this is experimentally difficult as production cross section are small and the nuclei are short-lived.

2. Low-Lying Isomers in the Odd-Odd ^{80,84}Y Isotopes

2.1 New Isomer in ^{80}Y

A new β-decay experiment has been performed to study the low-spin structure of the $N = Z + 2$ nucleus ^{80}Y. The ^{80}Y source has been produced via the fusion-evaporation reaction ^{24}Mg(^{58}Ni,pn) reaction at 190 MeV. The use of inverse kinematics provided a strongly forward-peaked recoil spectrum best suitable for an efficient collection and subsequent separation by the Argonne fragment mass analyzer [12]. The $A = 80$ mass separated recoils were implanted on a plastic tape and transported to a β- and γ-ray counter station consisting of three Ge detectors and a low-energy photon spectrometer. Each γ-ray detector had a thin plastic scintillator in front for the detection of β rays. The recoils were implanted within a deposition time of 20 s and their radioactive decay was subsequently measured for 20 s. Several cycles were also performed with 60 s deposition time and 60 s counting time. More experimental details have been reported in Ref. [13].

A single γ-ray spectrum recorded with the low-energy photon spectrometer and representative for the decay of the short-lived mass 80 recoils is displayed in Fig. 1. The strongest γ-ray peak has been identified as the $2^+ \rightarrow 0^+$ transition in ^{80}Sr. Further, a new γ-ray transition at 228.5 keV has been found [13] which is the second strongest line in the spectrum. This transition depopulates a new isomer in ^{80}Y with a half-life of 4.7(3) s [13]. Spin and parity of the isomer has been determined to be 1^-. Thus, the isomer decays by a M3 transition to the 4^- ground state. The extracted M3 transition strength is 0.78(5) Weisskopf units. Most interestingly, the isomer undergoes β decay as well to low-lying states in ^{80}Sr [14], as can be seen in the decay scheme of the isomer given in Fig. 2, upper left-hand side. This conclusion has been drawn from two experimental facts: (i) The time distribution of the $2^+ \rightarrow 0^+$ 385.9 keV transition in ^{80}Sr does not show the expected delayed feeding by the 228.5 keV isomeric transition (as the $4^+ \rightarrow 2^+$ 594.8 keV transition does), i.e., the time distribution can be fitted well with a single exponential decay curve. This indicates that the delayed component is canceled out. (ii) The difference spectrum between early and late time correlated events exhibits a strong 385.9 keV transition. This spectrum is shown in Fig. 3. The spectrum has been generated by subtracting the time-γ events of the 15 s to 60 s time range (late events) from the time-γ events of the 0 s to 10 s range (early events). Further, events in the time range 10 to 15 s have been excluded (see inset of Fig. 3). For normalization, we assumed that the intensity of the 783.1 keV line depopulating the 6^+ state at 1763.7 keV in ^{80}Sr cancels out leading to a factor of 0.68. As a result a small intensity amount of the 594.8 keV line remains in the difference spectrum. This may indicate that the 1^- isomeric β decay is highly fragmented. The situation is similar to the 1^- ground-state β decay of ^{76}Rb [15]. The difference spectrum indicates, in addition to the strong 385.9 keV transition, a weak 1350.4 keV line. The same 1350.4 keV transition can be seen in the sum coincidence spectrum of the 756 and 1142 keV gates providing evidence for a level at 2492.5 keV. This level seems to be populated in the isomeric decay only and has probably a low spin.

The β-decay branch has been estimated to be about 19(2) %. This result has important consequences for calculations of the rp-process nucleosynthesis of ^{80}Kr

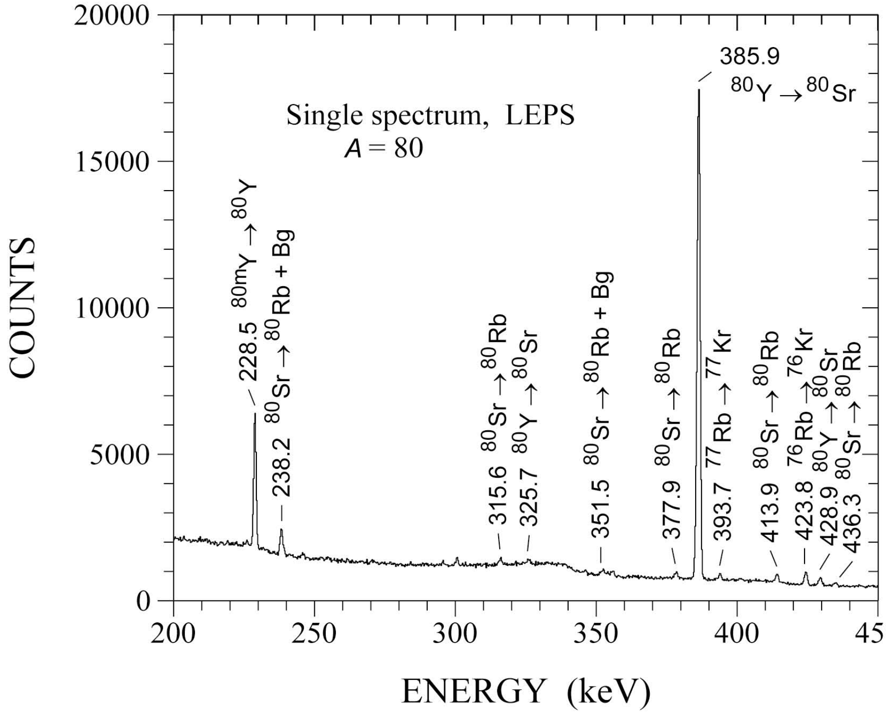

Fig. 1. Single γ-ray spectrum recorded with a low-energy photon spectrometer. The mass 80 recoils were mass separated by the Argonne fragment mass analyzer and transported to the counter station by a moving tape system. The figure has been taken from Ref. [13].

since the longer lived ground state of ^{80}Y ($T_{1/2}$ = 30.1(5) s [13]) is partly bypassed by the isomeric β decay, and a shorter effective half-life of ^{80}Y is obtained which leads to a reduction of the calculated overproduction of ^{80}Kr [10].

Total Routhian surface calculations [4] have shown that the odd-odd nucleus ^{80}Y exhibits a strongly deformed prolate shape with a quadrupole deformation of $\beta_2 = 0.37$ for the ground state. The prolate minimum persists up to high rotational frequencies. Thus, the deformed shape inspired the application of two-quasiparticle-plus-rotor calculations to investigate the wave functions of the low-lying states in terms of Nilsson orbitals. We found that the low-spin structure can be well explained if a proton-neutron residual interaction is employed. In this case the ordering of the states and the energy splitting between the 4^- ground state and the 1^- isomer can be well reproduced. The wave functions contain mainly the proton [422]5/2$^+$ and the neutron [301]3/2$^-$ Nilsson orbitals. These orbitals are coupled parallel and antiparallel in the 4^- ground state and in the 1^- isomer of ^{80}Y, respectively. The model calculations demonstrate that the deformed picture accounts very well for the observed properties of the low-lying states in ^{80}Y.

2.2 Low-Spin States in ^{84}Y

Early evidence was presented that the odd-odd nucleus ^{84}Y has very likely an 1^+ ground state and a higher-lying (5^-) isomer at an energy of about 500 keV [16,17]. This structure was deduced from early decay studies and the excitation energy of the isomer was an estimate only. Also, a few γ rays had been previously assigned to the ^{84}Zr decay [18], however, not placed into a level scheme. Therefore, three new decay experiments have been carried out: (i) via the irradiation of a ^{58}Ni target with ^{28}Si ions at 97 MeV using a modified NORDBALL setup [19], (ii) via the irradiation of a ^{58}Ni target with 99 MeV ^{28}Si ions and (iii) via the irradiation of a ^{58}Ni target with 135 MeV ^{32}S ions [20]. The latter two experiments were performed at Florida State University. In the first two experiments the chosen target-projectile combinations ensured that the even-even nucleus ^{84}Zr was produced in-beam, without any in-beam population of states in ^{84}Y and ^{84}Sr. In this way all states seen in these two latter nuclei were populated via the β-decay chain ^{84}Zr → ^{84}Y → ^{84}Sr only. The experiments at Florida State University were carried out with 5 Ge detectors and a low-energy photon spectrometer to detect the γ rays.

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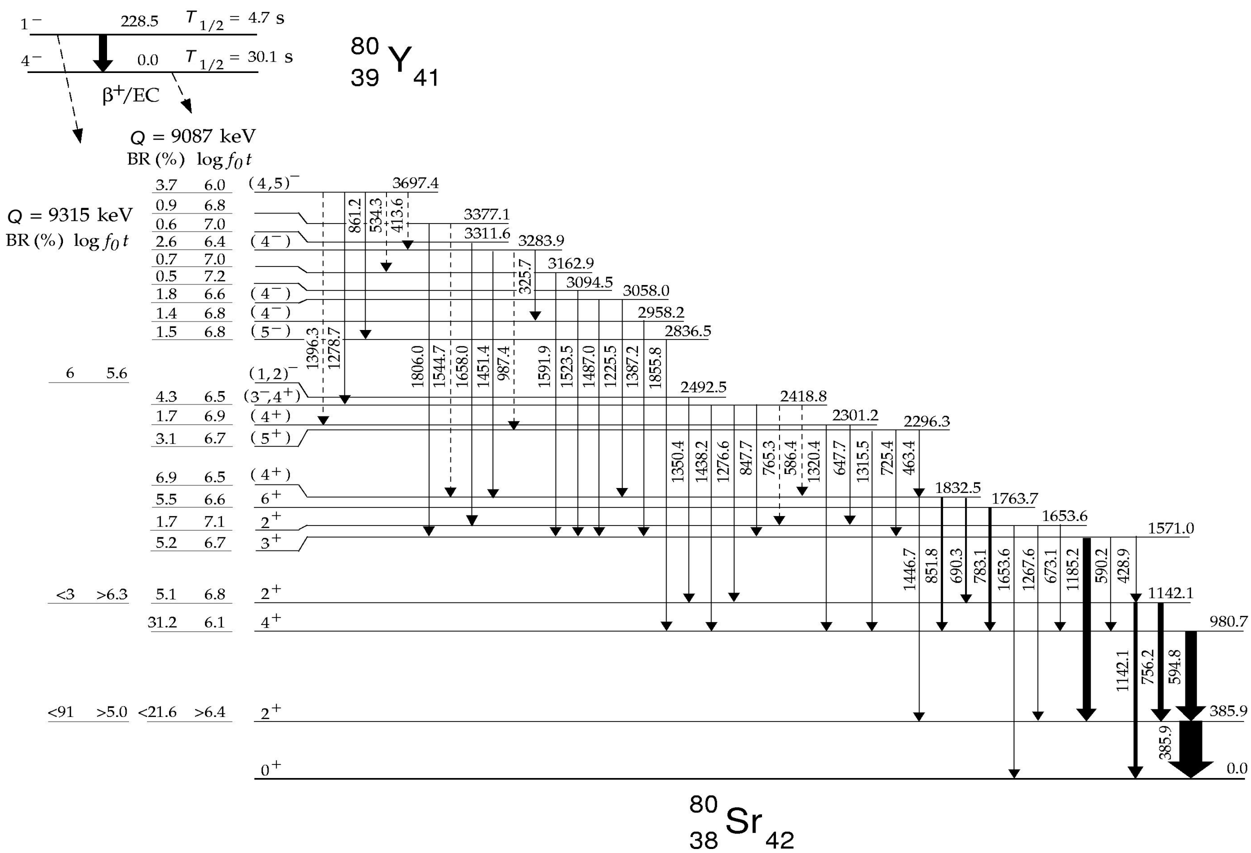

Fig. 2. Level scheme of ^{80}Sr deduced from the β decay of ^{80}Y. The figure has been taken from Ref. [14].

It has been found that the 1^+ isomer in ^{84}Y has an excitation energy of 67 keV and undergoes β decay only. No low-energy 67 keV γ transition to the ground state in ^{84}Y has been seen in the singles spectrum measured with the low-energy photon spectrometer. A partial decay scheme is shown in Fig. 4 where emphasis has been placed on the low-spin structure in ^{84}Y and the population of the 0^+ states in ^{84}Sr by the β decay of the 1^+ isomer. Further, states up to (7^+) in the γ-vibrational band of ^{84}Sr have been identified giving evidence for a possible spin and parity assignment of 6^+ to the ground state of ^{84}Y, in contrast to the previous assignment of (5^-) [17].

The new decay data revealed many new γ rays in ^{84}Y and ^{84}Sr and hence many new levels have been identified in both nuclei. For example, the previously reported excited 0^+ states at 1505 and 2075 keV in ^{84}Sr as identified via a (p,t) reaction [21] have been observed via γ-ray spectroscopy at 1504 and 2072 keV, respectively, for the first time. These states depopulate via 711 and 1279 keV transitions to the first excited 2^+ state at 793 keV in ^{84}Sr. An intense 793 keV peak has been seen only in the coincidence gates at 711 and 1279 keV indicating a very low multiplicity. Thus the origin is very likely a low-spin state in ^{84}Y, i.e., the β decay of the 1^+ isomer. The number of coincidence events of the 1279 keV line gated by the 793 keV transition in the 10 different detector-pair matrices of experiment (iii) was good enough to deduced angular correlation coefficients [22]. They provide evidence for a $0^+ \rightarrow 2^+ \rightarrow 0^+$ decay sequence.

3. Low-Lying States in Even-Even Neutron-Deficient Sr and Kr Isotopes

3.1 Excited 0^+ States in Sr Isotopes

The evolution of the nuclear shape from spherical to deformed in the even-even Sr isotopes is well known when moving away from the neutron shell closure at $N = 50$. These findings are based mainly on yrast level properties investigated via heavy-ion fusion-evaporation reactions. The study of non-yrast low-lying states may provide additional evidence to support these claims, or may indicate a more complex nuclear structure at low spins. The careful study of the β decay of odd-odd Y

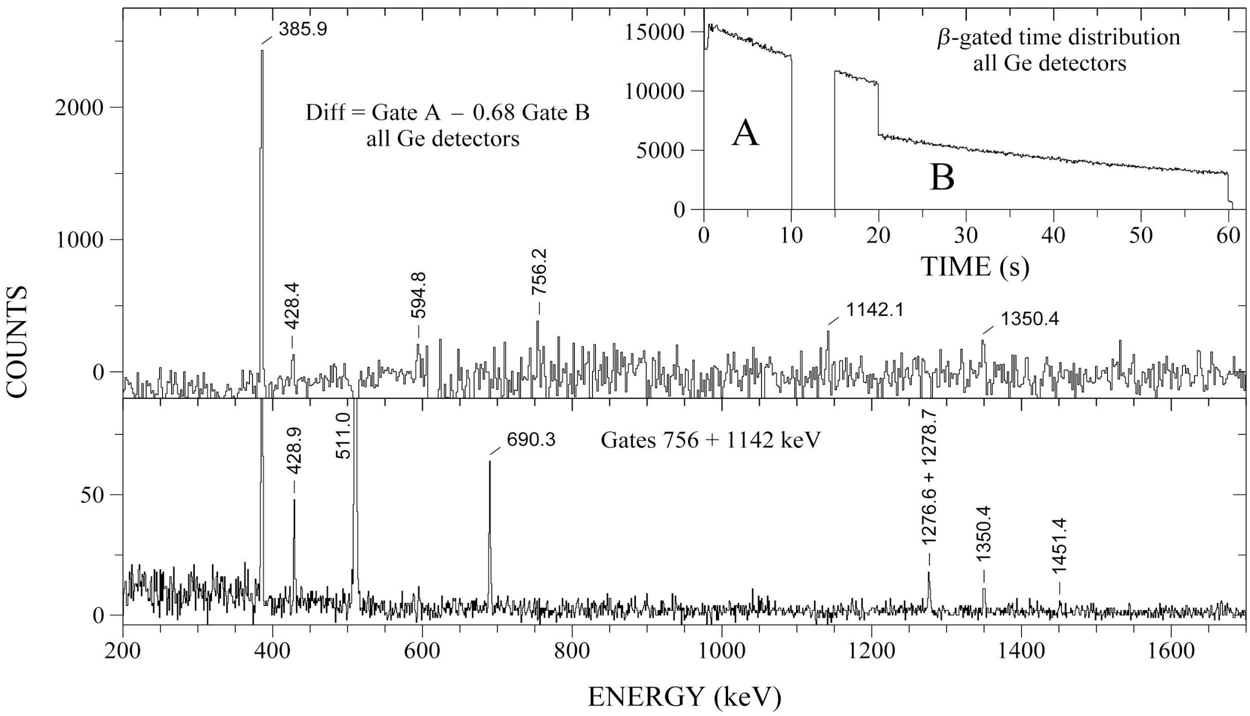

Fig. 3. Difference spectrum (top panel) of β-gated events from all Ge detectors to illustrate the decay of the 1^- isomer in ^{80}Y. The gating conditions are shown in the inset. To obtain the best possible statistics, the events from both 20 s and 60 s cycles have been added up causing the visible step at the time of 20 s. The 756 keV and 1142 keV background-corrected sum coincidence spectrum is shown in the bottom panel. The figure has been taken from Ref. [14].

study of the β decay of odd-odd Y nuclei seems to be the best method for populating non-yrast levels in neutron-deficient even-even Sr isotopes. Thus, the experiment described before for the investigation of an isomer in ^{80}Y has been analyzed for the $^{80}\mathrm{Y} \rightarrow {}^{80}\mathrm{Sr}$ β decay as well. The high selectivity of the Argonne fragment mass analyzer and the use of a multi-detector setup provided clean data. The known ^{80}Sr level scheme could be extended by 14 new levels [14], see Fig. 2. Spin and parity assignments are given based on the observed feeding and depopulation pattern, deduced log *ft* values, and on a comparison with the decay of the ^{78}Rb 4^- isomer to low-lying states in ^{78}Kr [23].

Most of the known excited 0^+ states in mass 80 nuclei have been identified via radioactive decay studies or particle-transfer reactions. The experimental detection is sometimes difficult since a $0_2^+ \rightarrow 0^+$ E0 transition can be verified only via a conversion electron measurement. Using γ-ray spectroscopy, usually the $0_2^+ \rightarrow 2_1^+$ E2 transition is detected. In general, the E0 matrix elements depend sensitively on the nuclear charge distribution and thus on the nuclear deformation [24]. Hence, the identification of these excited 0^+ states in a chain of isotopes allows to study the evolution of the nuclear shape at low spins. The latest results for the even-even Sr isotopes ($Z = 38$) are displayed in Fig. 5. The previously reported 0^+ states in ^{84}Sr, detected via particle-transfer reactions and confirmed by present γ-ray spectroscopy, are included. With decreasing neutron number, the position of the excited 0^+ states decreases as well and a multiplet-like grouping of the levels is obtained.

3.2 Excited 0^+ States in Kr Isotopes and N = 38 Isotones

The systematics of the excited 0^+ states in the neutron-deficient even-even Kr isotopes is plotted in Fig. 6. The recently discovered low-lying 0_2^+ state in ^{74}Kr, at most 85 keV above the first excited 2^+ state at 456 keV [25], refines the previously suggested shape coexistence picture [26]. This picture of a deformed-spherical shape coexistence was invoked to explain the irregularities in the energy spacings (or moments of inertias) of the lowest yrast excitations in the even-even ^{74,76}Kr nuclei. Now an oblate shape is suggested for the excited 0^+ state in ^{74}Kr, in contrast to the prolate deformed ground-state band. The half-life reported for the 0_2^+ in ^{74}Kr is the partial time for the E0 transition. The low-energy γ-ray decay has not been found yet.

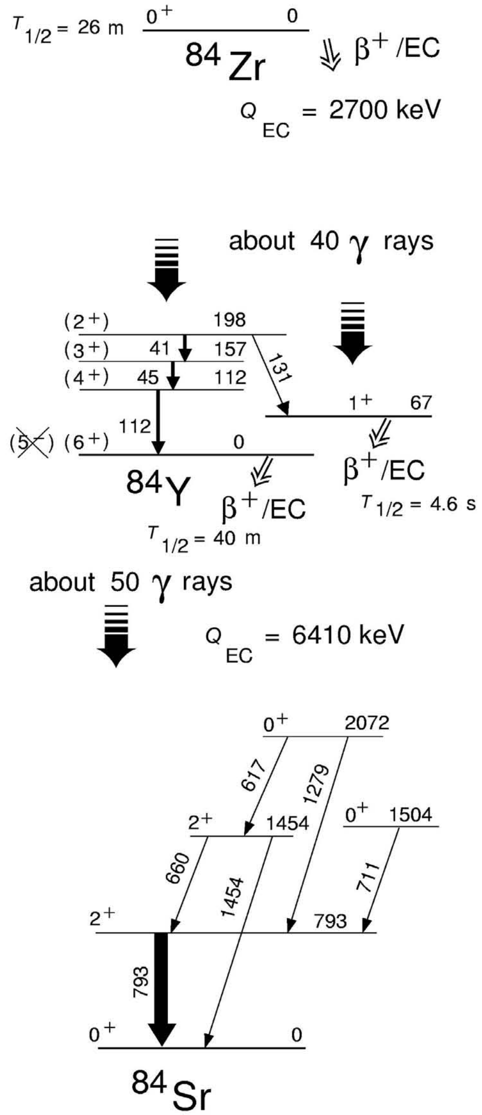

Fig. 4. Selected low-lying states in odd-odd ^{84}Y and even-even ^{84}Sr observed in β decay via the chain ^{84}Zr $\rightarrow$ ^{84}Y $\rightarrow$ ^{84}Sr using five Ge detectors and a low-energy photon spectrometer. The experimental results have been taken from Refs. [19,20].

It should be pointed out that the second 0^+ state in ^{74}Kr fits quite well into the $N = 38$ systematics as can be seen in Fig. 7. In most of these isotones, an excited 0^+ state has been found which decays by a low-energy γ ray to the first 2^+ state. The deduced $0^+_2 \rightarrow 2^+$ E2 transition strengths are in the order of 45 Weisskopf units indicating substantial collectivity. The reported E0 matrix elements are also given in the figure.

3.3 Vibration-Like Multiplets in Even-Even Sr Nuclei

As can be seen in Fig. 8, the new level scheme of ^{80}Sr deduced from our β-decay study is clustered into states typical of one-, two-, and three-phonon multiplets of an anharmonic vibrational nucleus. In this approach the lowest 2^+ state at 385.9 keV can be interpreted as an one-phonon vibrational state. States corresponding to the two-phonon triplet may be the observed states with spins 2^+_2 and 4^+_1 at energies of 1142.1 and 980.7 keV, respectively. From theoretical considerations there should also be a 0^+ state to complete the two-phonon triplet. A 0^+ level at 1.0 MeV was observed in a ^{78}Kr(^{3}He,n)^{80}Sr reaction study [29] but this level has not been seen in our decay data set. Based on a phenomenological parametrization of the effective interaction between phonons [30,31] and using experimental values for the interaction parameters as deduced from members of the observed three-phonon multiplet, a range of 820 keV to 880 keV can be estimated for the excitation energy of the two-phonon 0^+ state. For three phonons, the expected multiplet of levels consists of 0^+_3, 2^+_3, 3^+_1, 4^+_2, and 6^+_1. There are observed states with 2^+_3, 3^+_1, 4^+_2, and 6^+_1 at 1653.6 keV, 1571.0 keV, 1832.5 keV, and 1763.7 keV, respectively, which might be identified with these excitations. The expected 0^+_3 level has not been seen. Similar to the estimate of the excitation energy of the 0^+_2 state, an energy range of 1890 keV to 2270 keV can be deduced for the third 0^+ state based on the anharmonicity of the 2^+_2 state.

The observed vibrations in ^{80}Sr are clearly anharmonic since the $(2I + 1)$ weighted energy centroids of the known members of the multiplets are at 1036 keV and 1726 keV for $n = 2$ and 3, respectively, i.e., the higher orders (with $n = 2$, 3) are not strictly a multiple of the one-phonon energy of 386 keV. The deviations from the expected energies for a harmonic vibrator can be attributed to various anharmonic effects. One such anharmonicity may arise from a finite quadrupole deformationor angular momentum dependence of the nuclear shape. Much less anharmonicity is needed to understand the low-lying states in ^{84}Sr, as can be seen on the right-hand side of Fig. 8. In particular, the observed 0^+ states fit very well into this interpretation and complete the multiplets. The energy centroids of the $n = 2$, 3 multiplets are almost a multiple of the 793 keV ($n = 1$) energy. Thus, an almost harmonic vibration-like nature in ^{84}Sr is deduced.

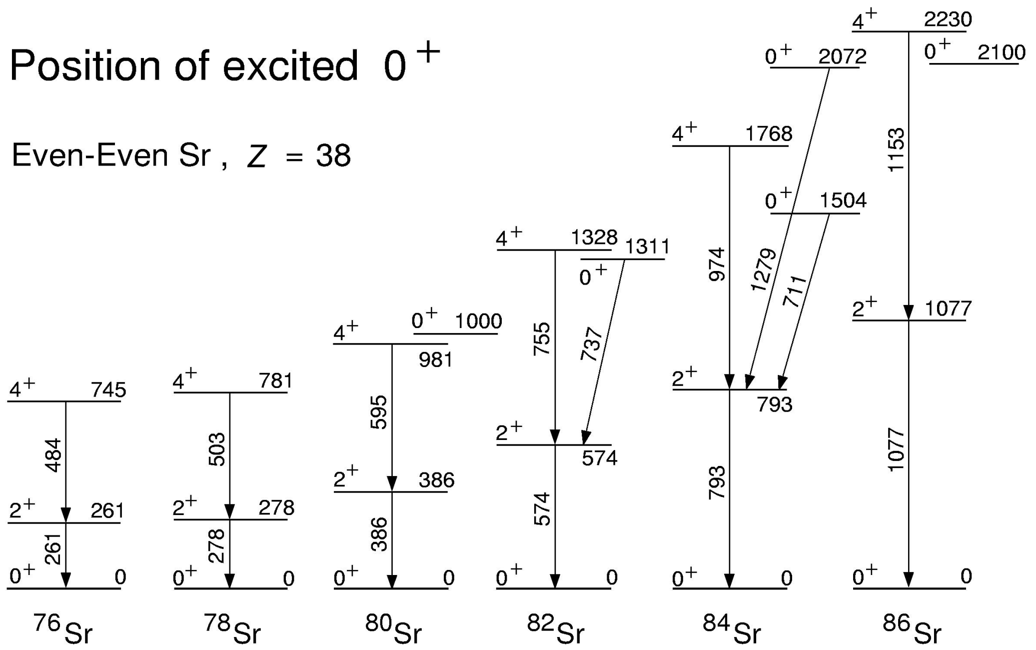

Fig. 5. Excited 0^+ states and the lowest yrast excitations are displayed for even-even neutron-deficient Sr isotopes. The experimental results on the 0^+ states have been taken from: ^{80}Sr, Ref. [29]; ^{82}Sr, Ref. [17]; ^{84}Sr, Refs. [20,21]; ^{86}Sr, Ref. [21].

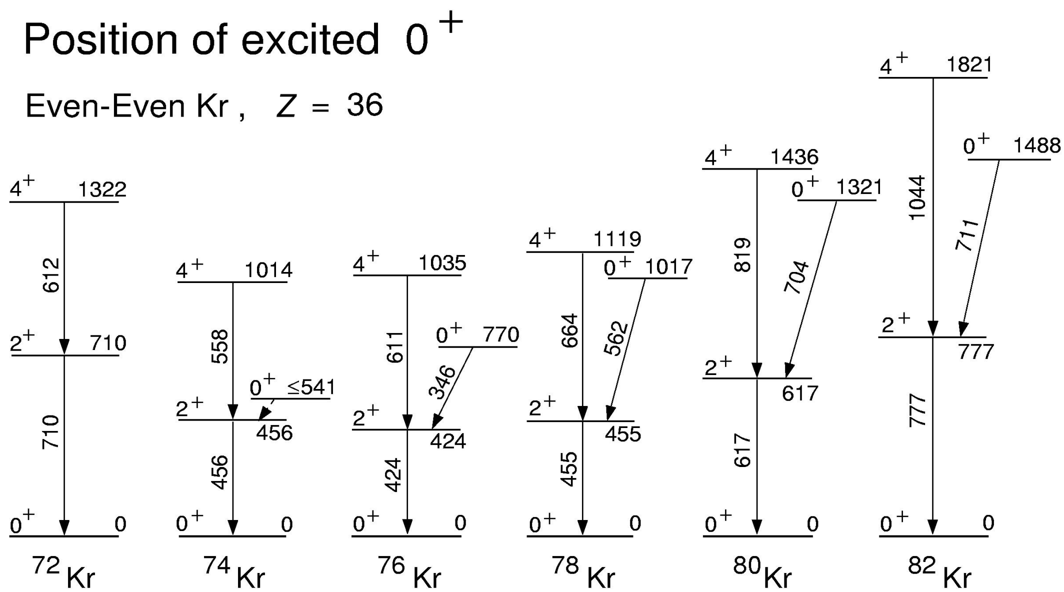

Fig. 6. Excited 0^+ states and the lowest yrast excitations are displayed for even-even neutron-deficient Kr isotopes. The experimental results on the 0^+ states have been taken from: ^{74}Kr, Ref. [25]; ^{76,78,80,82}Kr, Ref. [17].

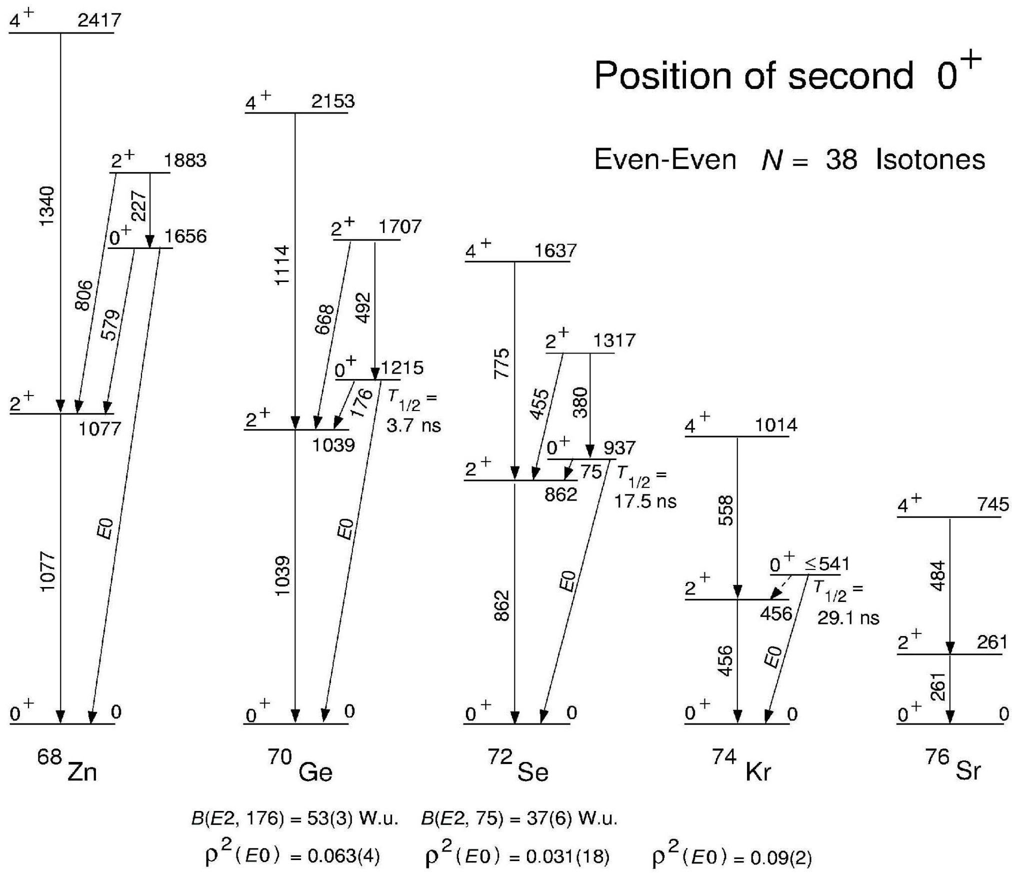

Fig. 7. Excited 0^+ states in some neutron-deficient $N = 38$ isotones. The experimental E2 and E0 transition strengths are given. The data have been taken from: ^{70}Ge, Ref. [27]; ^{72}Se, Ref. [28]; ^{74}Kr, Ref. [25].

4. Summary and Conclusions

Modern β-decay experiments employing multi-Ge detector and scintillator arrays combined with in-flight mass separation of recoils produced via nuclear reactions provide a very sensitive tool for the investigation of low-spin states in nuclei far off the line of stability. This has been demonstrated by the recent results obtained for the highly-fragmented radioactive decay of ^{80}Y $\rightarrow$ ^{80}Sr. In general, the new decay data suggest that the low-lying structures of ^{80,84}Sr show many vibration-like features in a potential with modest deformation including candidates for two- and three-phonon multiplets. This vibration-like nature seems to evolve to a more rotational behavior with increasing angular momentum and decreasing neutron number.

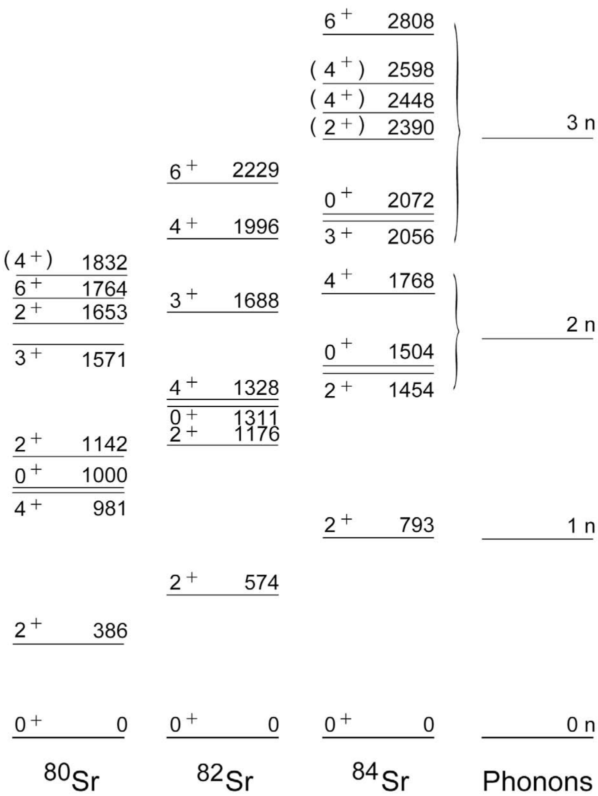

Fig. 8. Low-lying levels in the even-even ^{80,82,84}Sr isotopes. The level energies indicate the vibration-like multiplet structure. For ^{84}Sr, the multiple one-phonon energies are given on the right-hand side.

Acknowledgments

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